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RESEARCH MEMORANDUM

AN EVALUATION OF TURBOJET ENGINE THRUST CONTROL BY
EXHAUST-NOZZLE-AREA MODULATION AND COMPRESSOR-
INLET THROTTLING

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RESEARCH MEMORANDUMAN EVALUATION OF TURBOJET ENGINE THRUST CONTROL BY EXHAUST-
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SUMMARY

An experimental investigation was conducted at sea-level static conditions to determine the thrust control possible with a modern axial-flow turbojet engine at rated engine speed by employing compressor-inlet throttling in conjunction with exhaust-nozzle-area modulation.

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A thrust reduction of 38 percent of rated thrust was obtained with an exhaust nozzle area 45 percent greater than rated area. A thrust reduction of 61 percent of rated thrust was obtained by combined throttling of the engine inlet to produce a 31 percent pressure drop and use of the increased exhaust-nozzle area of 45 percent. Thrust reduction available from both exhaust-nozzle-area modulation and compressor-inlet throttling was predictable (as based on simple cycle analysis with constant efficiencies and with air flow directly proportional to changes in engine inlet pressure) for this engine within an accuracy of 4 percent.

INTRODUCTION

The ever-increasing flight velocity of jet-propelled aircraft has made deceleration for landing a major operational problem. In the landing operation, engine thrust must be greatly reduced, and it is desirable that full engine thrust be obtainable instantaneously in case of an aborted landing. Because thrust control available by varying the engine speed is relatively slow, other more responsive methods have been sought. References 1 and 2 discuss the advantages of operating the turbojet engine at rated speed and controlling thrust by exhaust-nozzle-area modulation. These references report that the 6 or 7 seconds required to increase thrust from 50 to 100 percent by varying engine speed can be reduced to as little as 1 second by the use of exhaust-nozzle-area modulation. In some applications, however, 50 percent thrust regulation is insufficient. A brief investigation was therefore conducted at the NACA Lewis laboratory to evaluate the effectiveness of compressor-inlet throttling used in conjunction with exhaust-nozzle-area modulation as a method of further reducing thrust. Data were obtained on a current

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production-type turbojet engine at sea-level static conditions for three fixed-area exhaust nozzles and a series of compressor-inlet screen configurations. A comparison of the experimental results with calculated results was made and is presented herein.

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APPARATUS

Engine and Installation

The engine used in this investigation was a current production-type turbojet engine having a sea-level static thrust of 5970 pounds at a rated engine speed of 7950 rpm, an exhaust-gas temperature of 1275° F, and an inlet-air temperature of 60° F. The engine is composed of a 12-stage axial-flow compressor, eight can-type combustors, and a single-stage turbine.

The turbojet engine was mounted on a thrust measuring bed in a sea-level test cell (fig. 1). A diaphragm-type seal mounted around the tail pipe at the exhaust-nozzle inlet isolated the test cell from the exhaust chamber. Engine air was ducted into the airtight test chamber through an air-measuring nozzle, and a can-type combustor was used as a preheater in order to maintain a given engine-inlet-air temperature.

Screens

The location of the screens at the compressor inlet is shown in figure 2. Wire mesh size, diameter, and solidity are tabulated in the following table and actual size photographs of the screens are shown in figure 3.

Screen configuration	Mesh, wires per in.	Wire diameter, in.	Solidity
1 (backing)	$1\frac{1}{3}$ by $1\frac{1}{3}$	0.091	0.228
2	2 by 2	.051	.194
3	14 by 18	.011	.321
4	4 by 4	.047	.341
5	28 by 30	.013	.613

The screens were mounted at a flange location in the engine inlet duct, and the outer edge of the screens was supported by bolting between

the flanges. The inner edge of the screen was bolted to a 3/4-inch angle iron ring which was fastened to the accessory housing. A so-called backing screen (0.091 in. wire diameter) was used in all instances for structural support of the other screens.

Instrumentation

The location of pressure and temperature instrumentation through the engine is shown in figure 2. All thermocouples and total-pressure probes were located on centers of equal areas. The engine-inlet total pressure was not measured but was assumed to be equal to the cell static pressure. Static pressure at the exhaust-nozzle exit was measured by three open-end tubes installed in the sound-muffling chamber in the plane of the exhaust-nozzle exit. Air flow was measured by a 26-inch-long radius A.S.M.E. air-measuring nozzle in the main air supply duct and by a flat-plate orifice in the preheater air supply line (fig. 1).

PROCEDURE

For the purpose of this investigation, the rated performance of the engine was assumed to be at an engine speed of 7900 rpm and a turbine-outlet temperature of 1710° R. Data were obtained over a range of engine speeds for each combination of exhaust-nozzle area and inlet screen configuration presented in the following table:

Nozzle area, percent of rated			Screen configuration
100	128	145	None
	128	145	1
	128	145	1 and 2
	128	145	1 and 3
	128	145	1, 2 and 4
		145	1 and 5

The engine-inlet-air temperature was held constant at 100° F. Normal ambient air temperature plus temperature rise in the test cell would not permit a lower temperature to be maintained.

The blockage of the initial screen configuration (configurations 1 and 2) was determined by using data from reference 3, and blockages of subsequent screen combinations were chosen to approach limiting turbine-outlet temperature (1710° R) at rated speed (7900 rpm) with each of the oversized exhaust nozzles.

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RESULTS AND DISCUSSION

Thrust Reduction with Exhaust-Nozzle-Area Modulation

The effect of exhaust-nozzle-area modulation on thrust loss at rated speed is shown in figure 4. The exhaust-nozzle areas presented in this figure and in all subsequent figures are effective areas. The areas were computed from thrust, mass-flow, temperature, and pressure measurements. Actual areas were not used because of the blockage effects of the nozzle-exit instrumentation. As shown in figure 4, the rate of increase of thrust loss decreases as exhaust-nozzle area is increased. With a nozzle-area increase of 45 percent, a decrease in thrust of 38 percent was obtained. The solid curve is the calculated variation of thrust with nozzle area for this engine at sea-level static conditions and a 100° F inlet-air temperature. As the nozzle area is increased from rated area, the pressure level in the engine and the turbine-outlet temperature both decrease until turbine limiting loading is reached. As the nozzle area is further increased, the engine pressure level continues to decrease but the turbine-outlet temperature no longer drops. A detailed discussion of the method of calculation is presented in the appendix. All computed curves are based on simple cycle analysis with air flow directly proportional to changes in engine inlet pressure. The experimental results of this investigation are within 3 percent of the calculated results.

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The dashed curve of figure 4 presents data from reference 1 for a similar engine at a flight Mach number of 0.21 over a range of altitudes from 15,000 to 45,000 feet. At these flight conditions, an increase in nozzle area of 45 percent gave a thrust decrease of 47 percent. The difference between the solid and dashed curves is believed due to Mach number effects and the possibility that the engine used in reference 1 had turbine limiting loading characteristics different from those of the engine used in the present investigation.

Thrust Reduction by Combined Inlet Throttling and Exhaust-Nozzle-

Area Modulation

Thrust reduction by inlet throttling must be combined with exhaust-nozzle-area modulation whenever operation with an unchoked exhaust nozzle is encountered in order to prevent the turbine-inlet temperature from exceeding the established limit. For the engine used in this investigation, the exhaust nozzle was unchoked over the entire range of operating conditions covered. The effect of inlet throttling on reduced thrust ratios at rated engine speed for the three exhaust-nozzle sizes is presented in figure 5. The inlet throttling was accomplished by means of various inlet screen configurations as outlined in the PROCEDURE, and the total-pressure drop across the screens was computed from static-pressure measurements at stations 1a and 1b. The loss in thrust with

inlet throttling results from a decrease in engine air flow and exhaust-nozzle pressure ratio. The use of inlet throttling increased the thrust loss with nozzle configuration A from 30 percent to 51 percent and with nozzle configuration B, from 37 percent to 61 percent with the maximum thrust reduction for each nozzle area being at limiting turbine-outlet temperature.

3376 The effect of inlet pressure loss on turbine-outlet temperature is shown in figure 6. With constant exhaust-nozzle area and constant engine speed, the turbine-outlet temperature with an unchoked exhaust nozzle increases with inlet pressure loss. A decrease in inlet pressure results in a proportional decrease in air flow, and when the exhaust nozzle is choked, a proportional decrease in nozzle inlet pressure. However, if the required mass flow is to be passed through an unchoked nozzle, the nozzle inlet pressure cannot decrease in direct proportion to the inlet pressure because flow through an unchoked nozzle depends on both nozzle inlet pressure and pressure ratio. The result is an increase in engine pressure ratio and a decrease in turbine pressure ratio. To maintain speed with the lower turbine pressure ratio requires an increase in turbine inlet temperature and hence in turbine outlet temperature.

The combined effects of inlet pressure loss and exhaust-nozzle-area modulation on reduced thrust ratio at rated speed and limiting turbine-outlet temperature are presented in figure 7. Along with the total reduction in thrust, the incremental reductions due to both change in air flow and change in engine pressure ratio for experimental and computed results are shown. The reduction of thrust with inlet pressure loss is merely a pressure effect because the thermodynamic cycle from inlet to exhaust remains unchanged except for pressure level providing engine speed and turbine-outlet temperature are maintained constant. As stated in reference 4, air flow is directly proportional to inlet pressure and thrust is directly proportional to air flow. Thrust is also proportional to the exhaust-nozzle pressure ratio, and the proportionality depends on the magnitude of the exhaust-nozzle pressure ratios encountered. With the preceding information and the value of exhaust-nozzle pressure ratio at rated engine conditions, the thrust loss was calculated for combined inlet throttling and exhaust-nozzle-area modulation. The experimental results of this investigation agreed within 4 percent of the calculated thrust loss.

Exhaust-Nozzle-Area Modulation Required with Inlet Throttling

When utilizing a system of exhaust-nozzle-area modulation and inlet throttling, consideration must be given to the proper matching of inlet screens to exhaust-nozzle size if maximum thrust control is to be obtained. Presented in figure 8 is a computed curve (with experimental points

plotted thereon) showing the variation of exhaust-nozzle area with inlet pressure loss at rated engine speed and turbine-outlet temperature. The curve was computed assuming that both air flow and nozzle inlet pressure were directly proportional to changes in engine inlet pressure. In this case, nozzle inlet pressure can be assumed proportional to engine inlet pressure because turbine discharge temperature, engine temperature ratio, and therefore engine pressure ratio are constant. Figure 8 indicates that for this engine, an engine inlet pressure loss of about 35 to 38 percent is maximum for exhaust nozzles of practical size.

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CONCLUDING REMARKS

The results of this investigation of turbojet engine thrust control show that at rated engine speed the thrust can be reduced 38 percent if the exhaust-nozzle area is increased 45 percent, and that the thrust can be further reduced to a total of 61 percent if inlet throttling is used in conjunction with the increased exhaust-nozzle area. The inlet total-pressure drop necessary to produce this reduction is 31 percent.

Thrust losses from both exhaust-nozzle-area modulation and compressor-inlet throttling were predictable (based on simple cycle analysis with constant efficiencies and with air flow directly proportional to changes in engine inlet pressure) for this engine within an accuracy of 4 percent.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 17, 1954

APPENDIX - SYMBOLS AND METHODS OF CALCULATION

Symbols

The following symbols are used in this report:

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- A area, sq ft
- F thrust, lb
- P total pressure, lb/sq ft
- T total temperature, °R
- W weight flow, lb/sec

Subscripts:

- g gas
- n normal rated conditions

Numbered subscripts refer to instrumentation stations within the engine (fig. 1).

Method of Calculating Thrust Variation with Exhaust-

Nozzle-Area Modulation

Calculating the variation of thrust with exhaust-nozzle area involved a cycle analysis of the engine based on rated conditions. In making the calculations, constant air flow, constant compressor and turbine efficiencies, and a choked turbine stator were assumed. Because of the assumption of constant air flow, this method of calculation is restricted to engines which display relatively minor variations of air flow with compressor pressure ratio at a given engine speed.

The compressor efficiency of the engine used was computed from pressure and temperature measurements at stations 1 and 3 (fig. 2). The turbine-inlet temperature was computed by using the temperature obtained at station 5 and the knowledge that the turbine work was equal to the compressor work. The turbine efficiency was then determined from the temperatures and pressures at stations 4 and 5. The combustor pressure

drop $\frac{P_3 - P_4}{P_3}$ and the tail-pipe pressure drop $\frac{P_5 - P_6}{P_5}$ were determined and assumed to remain constant as exhaust-nozzle area was increased.

Instead of computing thrust for a range of assumed exhaust-nozzle area ratios, a range of turbine-inlet temperatures was assumed and the thrust and exhaust-nozzle-area ratio were computed from the resulting temperatures and pressures. Since the turbine stator was choked,

$$\frac{W_{g,4}\sqrt{T_4}}{P_4 A_4} = \text{constant}$$

where A_4 is the throat area of the turbine stator. Since A_4 is constant and $W_{g,4}$ is essentially constant, P_4 is directly proportional to the square root of the turbine-inlet temperature. Therefore turbine-inlet pressures were determined for the range of assumed turbine-inlet temperatures. Compressor discharge pressures P_3 were determined by correcting P_4 for the combustor pressure drop. Compressor work was determined from P_3 and the original compressor efficiency. Since compressor work is equal to turbine work, T_5 could be computed, and using the original turbine efficiency, P_5 was computed. P_6 was determined by correcting P_5 for the tail-pipe pressure loss, and T_6 was assumed equal to T_5 . The new thrust and exhaust-nozzle area were then determined from T_6 , P_6 , $W_{g,6}$, and ambient pressure. 3576

This method of computation is good only up to the point where turbine limiting loading is reached. Turbine limiting loading is the condition at which no further work can be obtained from the turbine regardless of increases in turbine pressure ratio. After turbine limiting loading is reached, conditions in the engine at station 4 and hence T_6 will no longer change as the exhaust-nozzle area is increased. Turbine limiting loading can be estimated by use of references 5 and 6, or it can be determined experimentally as was done in this investigation. It was found that as the exhaust-nozzle-area ratio was increased, T_6 remained constant at $1465^\circ R$ at all nozzle area ratios above 1.12. For conditions after turbine limiting loading was reached, thrust was computed from $T_6(1465^\circ R)$, $W_{g,6}$, ambient pressure, and a range of assumed exhaust-nozzle areas.

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6. English, Robert E., Silvern, David H., and Davison, Elmer H.: Investigation of Turbines Suitable for Use in a Turbojet Engine with High Compressor Pressure Ratio and Low Compressor-Tip Speed. I - Turbine-Design Requirements for Several Engine Operating Conditions. NACA RM E52A16, 1952.

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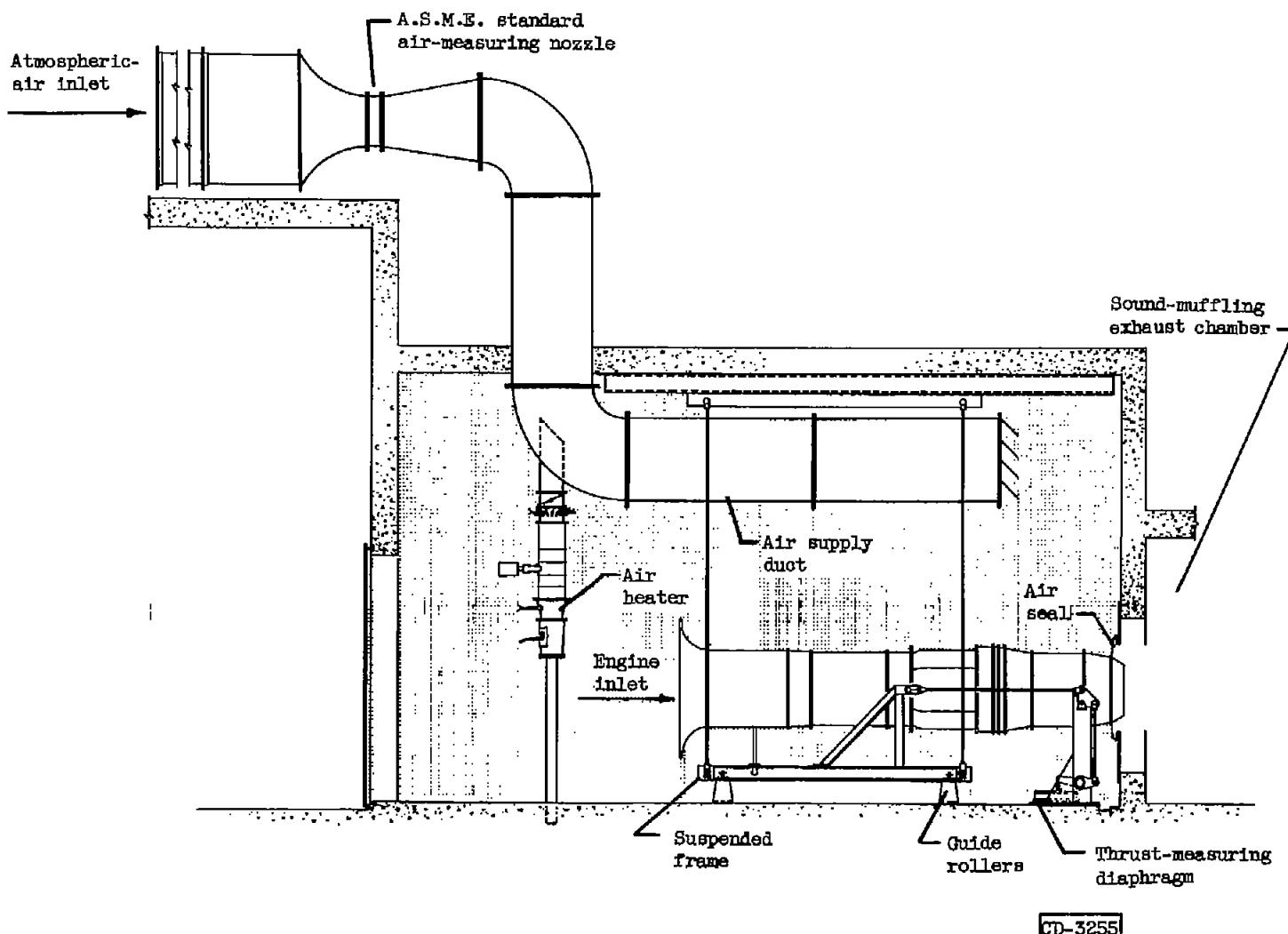
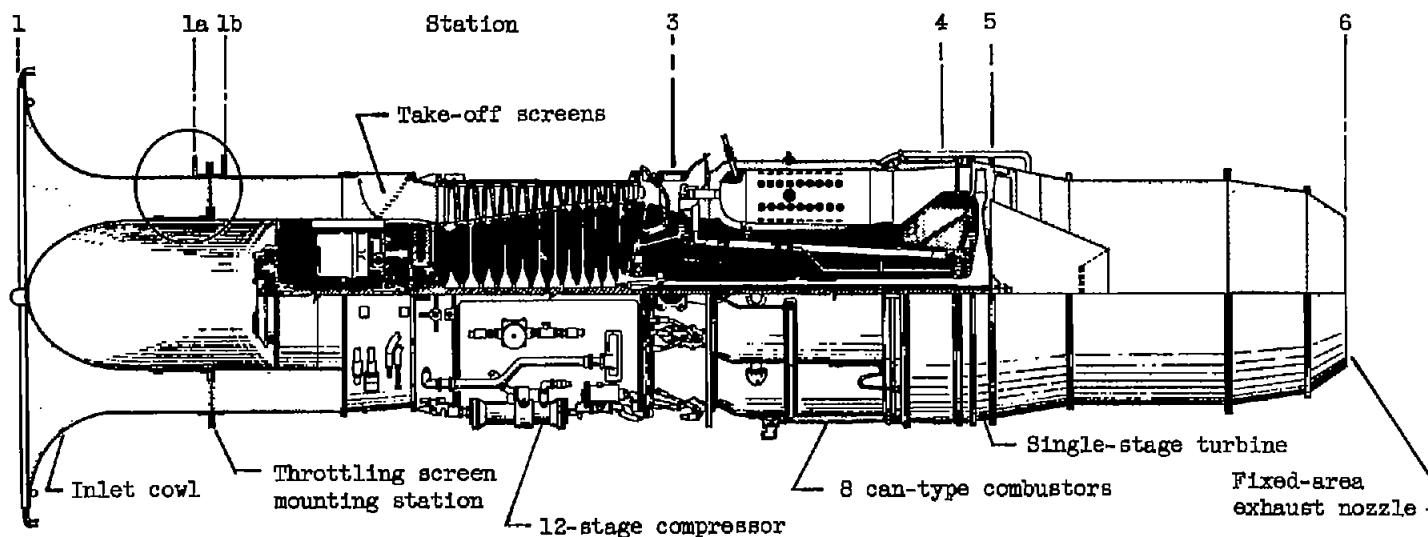
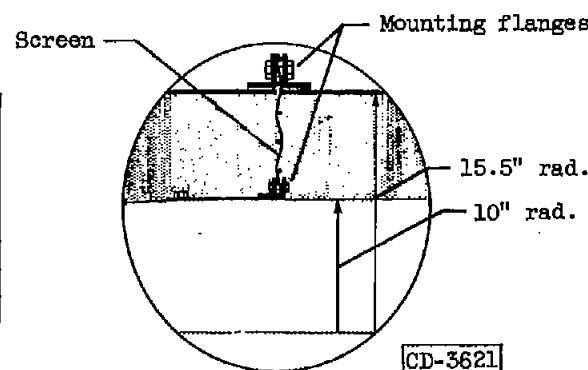


Figure 1. - Engine installation in test cell.

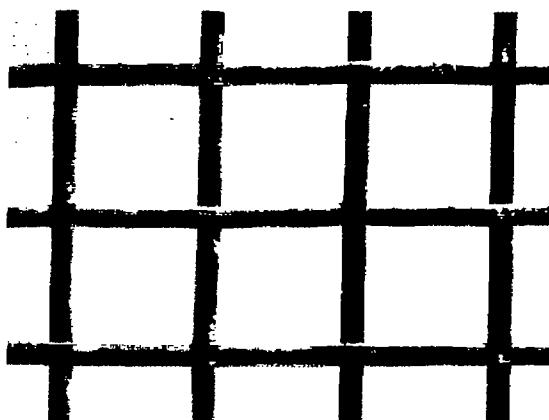


Instrumentation	Station						
	1	1a	1b	3	4	5	6
Total-pressure rakes	--	--	--	4	8	2	1
Total-pressure probes per rake	--	--	--	6	1	5	6
Thermocouple rakes	4	--	--	4	--	6	1
Thermocouples per rake	5	--	--	6	--	5	16
Wall static taps	--	3	3	4	--	2	--

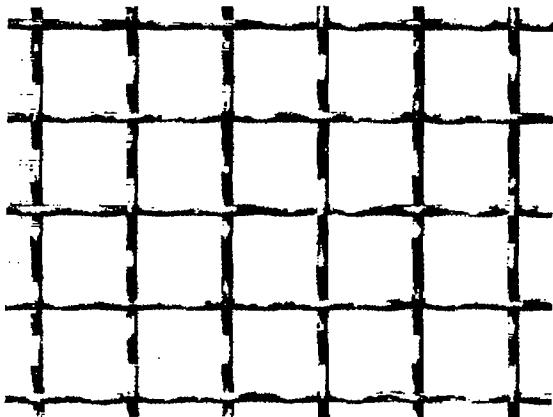


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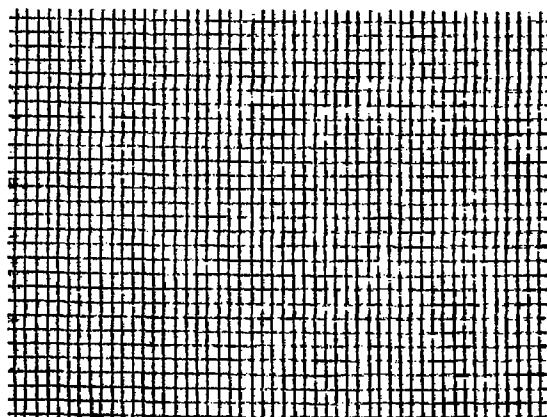
Figure 2. - Engine and instrumentation.



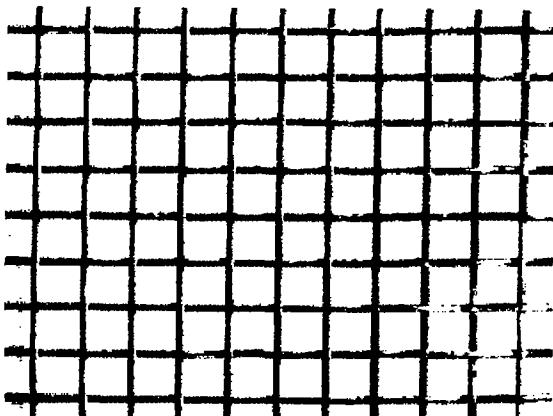
Configuration 1; $1\frac{1}{3}$ by $1\frac{1}{3}$ -inch mesh;
0.091 inch wire diameter.



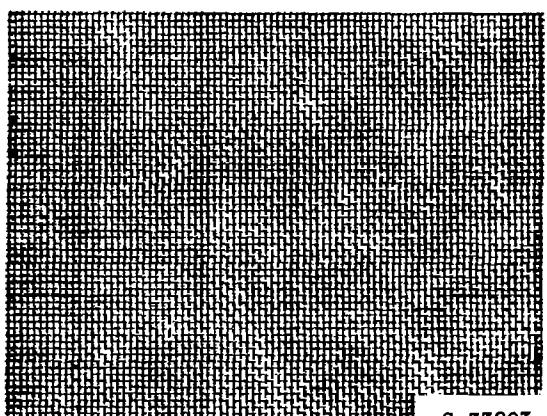
Configuration 2; 2- by 2-inch mesh;
0.051 inch wire diameter.



Configuration 3; 14- by 18-inch mesh;
0.011 inch wire diameter.



Configuration 4; 4- by 4-inch mesh;
0.047 inch wire diameter.



Configuration 5; 28- by 30-inch mesh;
0.013 inch wire diameter.

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Figure 3. - Photographs of screen configurations used (actual size).

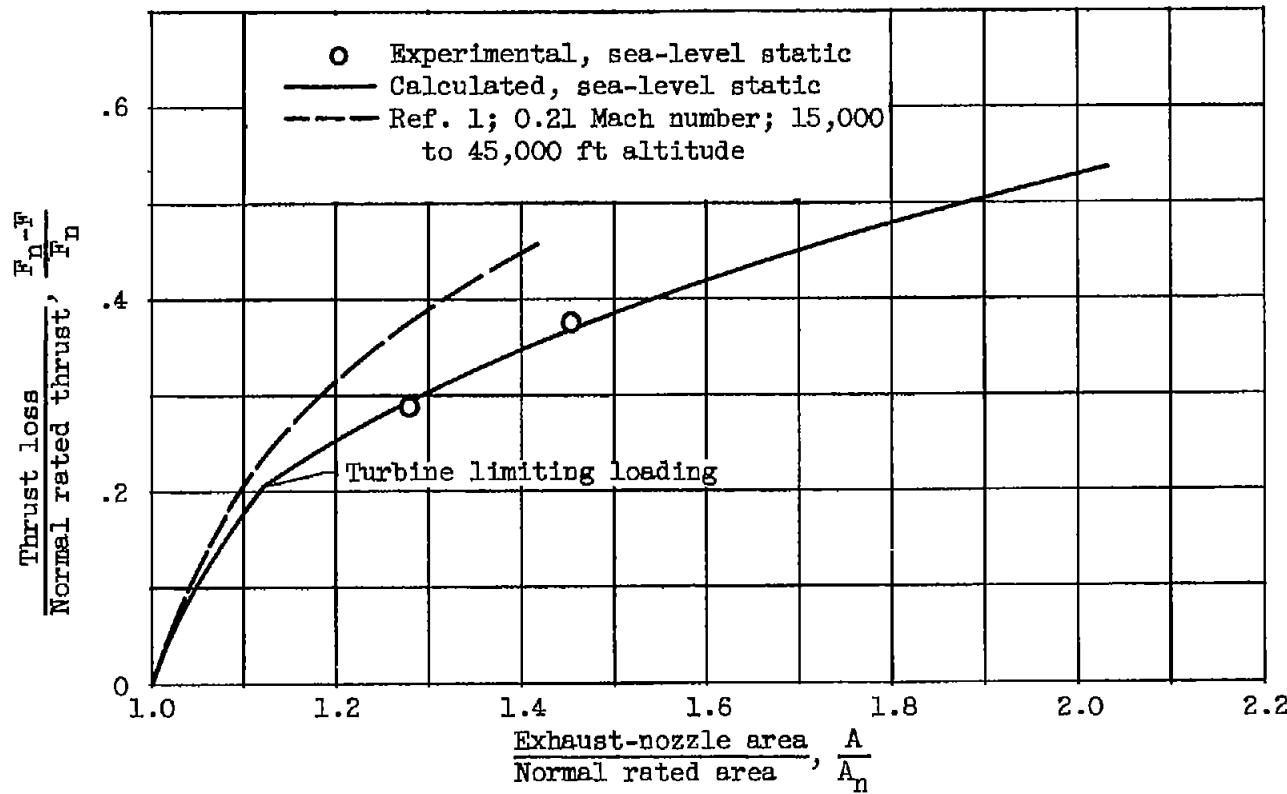


Figure 4. - Effect of exhaust-nozzle-area modulation on thrust loss at 7900 rpm (rated).

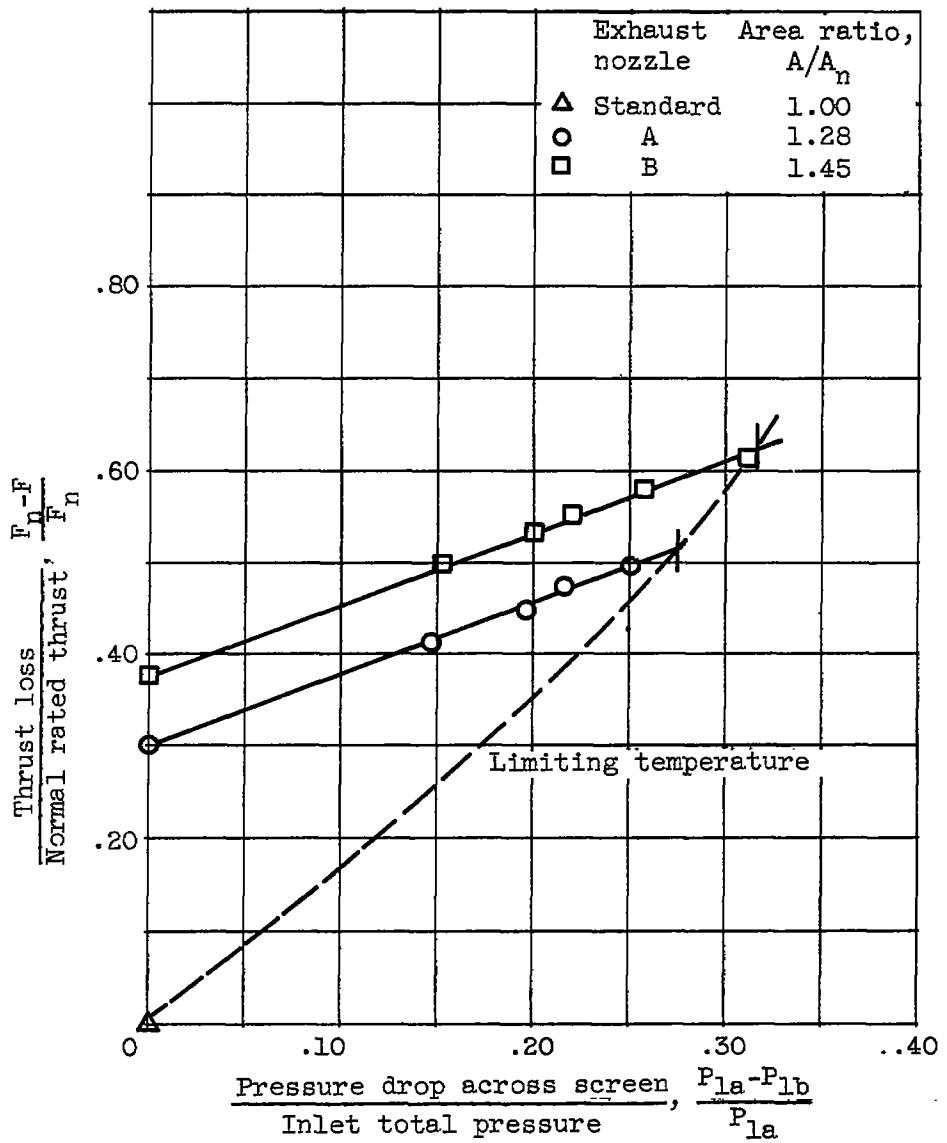


Figure 5. - Effect of screen pressure drop on thrust at 7900 rpm and several exhaust-nozzle sizes.

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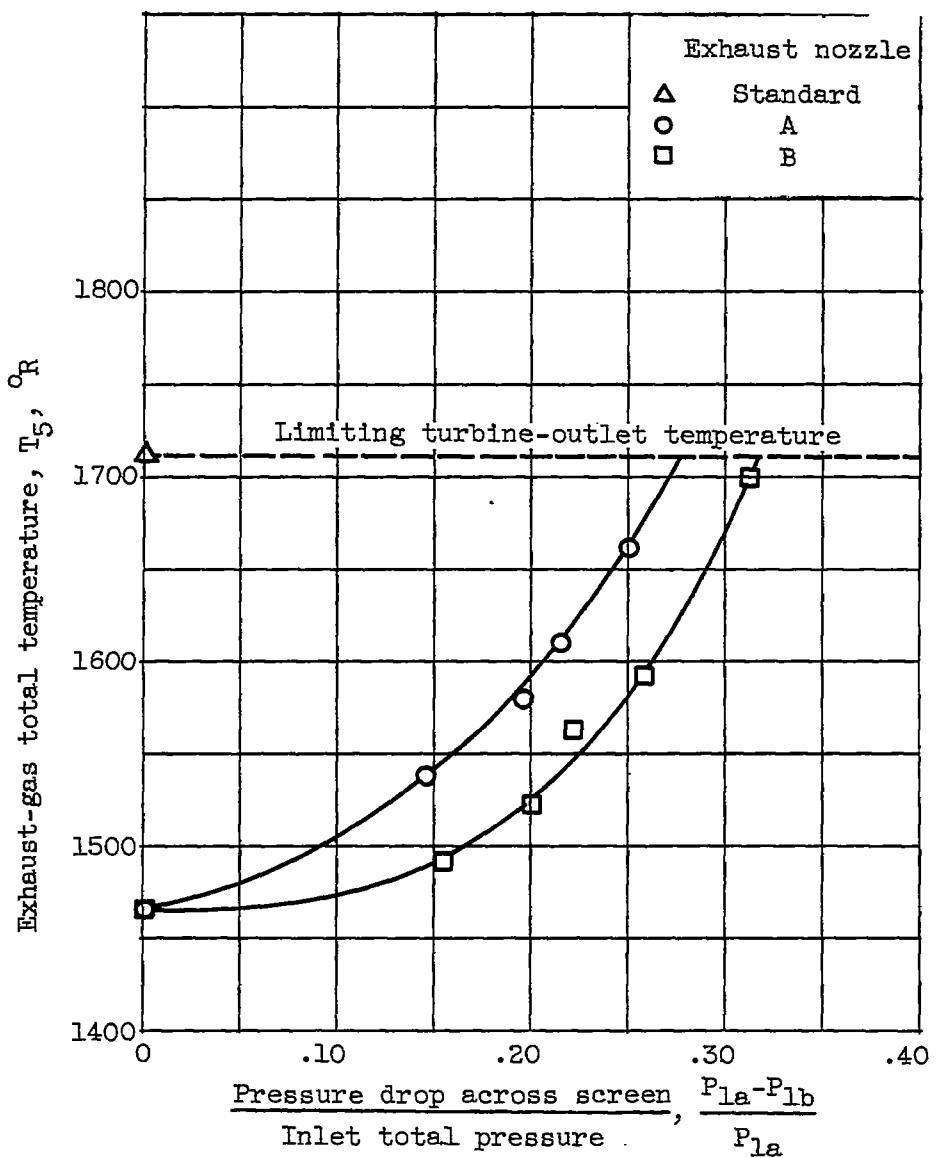


Figure 6. - Effect of screen pressure drop on exhaust-gas temperature at engine speed of 7900 rpm.

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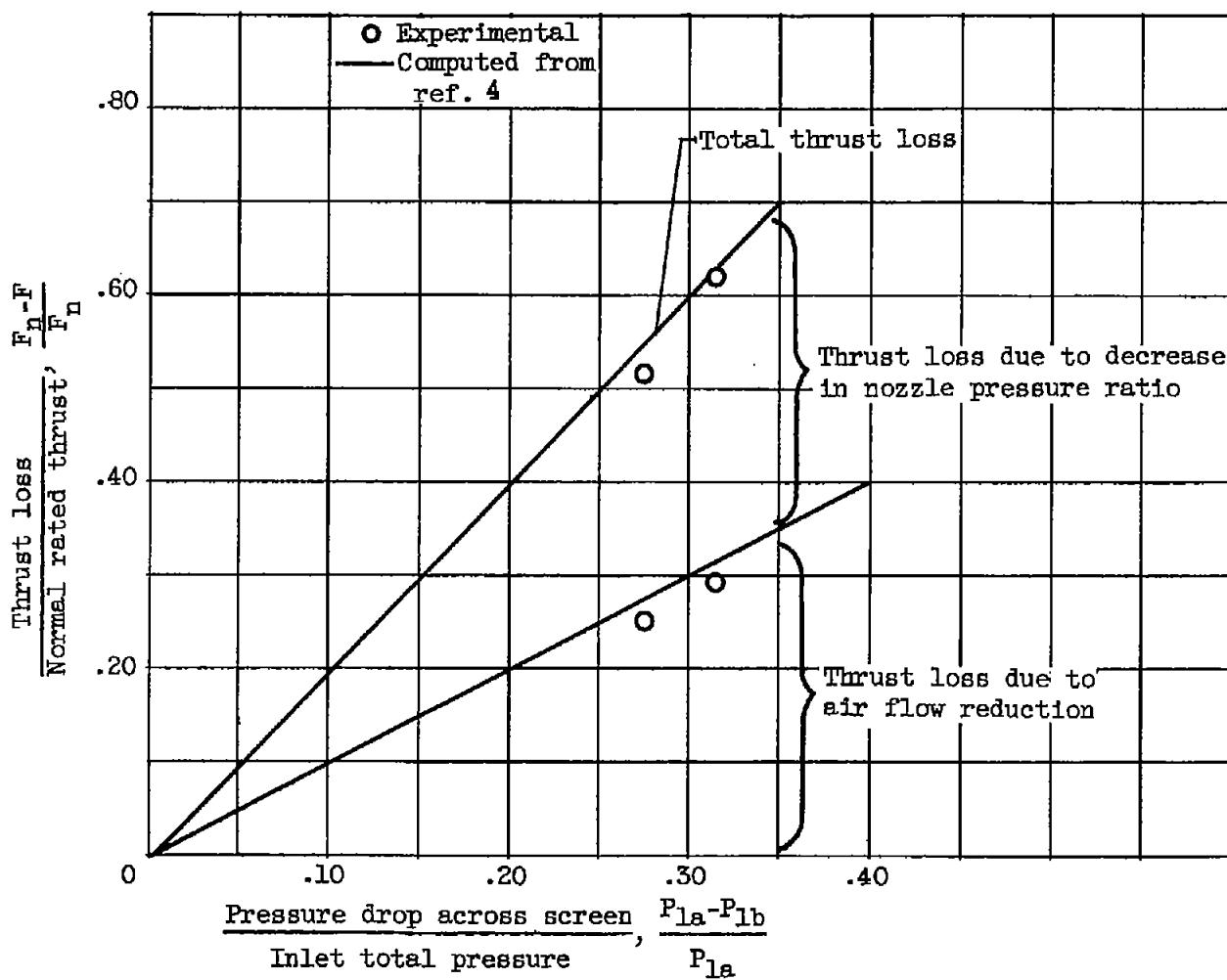


Figure 7. - Combined effects of screen pressure drop and exhaust-nozzle-area modulation on thrust loss ratio at rated speed and limiting turbine-outlet temperature.

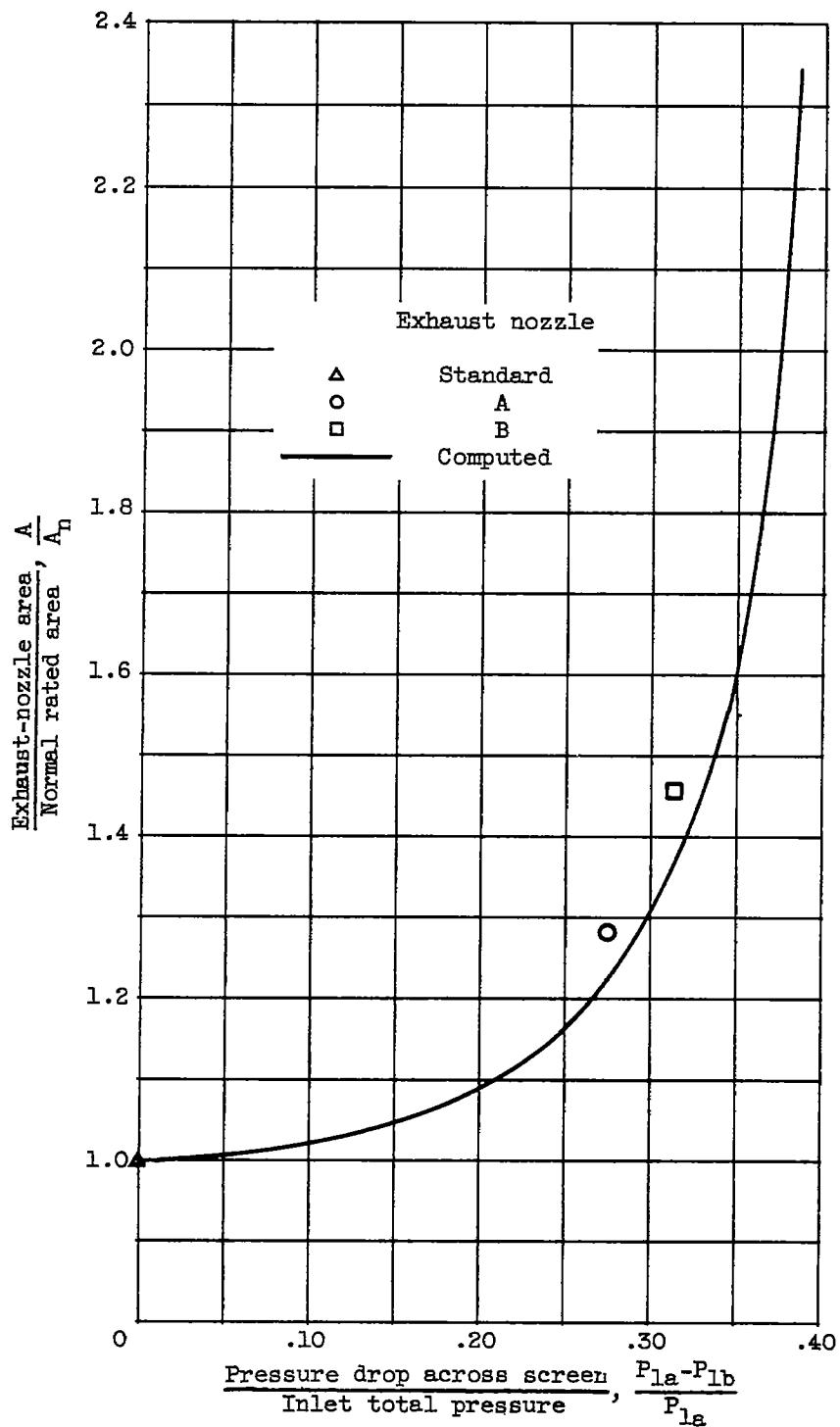


Figure 8. - Variation of exhaust-nozzle area with screen pressure drop for limiting temperature and rated speed.

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